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5200 CYCLE TEST OF AN 8-CM DIAMETER Hg ION THRUSTER

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ABSTRACT

An accelerated cycle test was conducted in which an 8-cm Engineering Model Thruster (EMT) prototype successfully completed 5200 on-off cycles and a total of more than 1300 hours of thruster operation at a 4.5 mN thrust level. Cathode tip heater powers required for starting and keeper voltages remained well within acceptable limits. The discharge chamber utilization and electrical efficiency were nearly constant over the duration of the test. It is concluded that on-off cyclic operation by itself does not appreciably degrade starting capability or performance of the 8-cm EMT.

INTRODUCTION

The 4.45-mN (1-mlb) 8-cm mercury ion Engineering Model Thruster (EMT) has been designed for long term stationkeeping of geosynchronous spacecraft. Thruster durability and starting reliability are critical requirements for such auxiliary propulsion applications. For example, a seven-year stationkeeping mission requires about 2500 on-off duty cycles and a total of 7500 hours of thruster operation.

Both 5- and 8-cm auxiliary propulsion ion thruster designs have been developed and tested (ref. 1). Foremost among these are the Structurally Integrated 5- and 8-cm Thrusters: forerunners of the 8-cm EMT. Life tests of the 5-cm (9700 hrs, ref. 2) and 8-cm (15 000 hrs, ref. 3) have successfully demonstrated sufficient lifetime to satisfy the durability requirements of the most probable auxiliary propulsion missions. Those life tests, however, consisted primarily of steady state thruster operation with limited cyclic operation. Thruster components have been individually life tested (refs. 4 and 5) and have also shown sufficient durability. Up to the present, the only cycle life testing had been with the 8-cm ion thruster cathodes (ref. 6), which successfully completed over 3000 cycles. Previously, no ion thruster of the auxiliary propulsion design had accumulated the number of cycles required to perform a long term stationkeeping mission. Cyclic operation imposes requirements on ion thruster components in addition to those for steady state operation.

It is therefore important and necessary to demonstrate that the ion thruster has the restart and cyclic capability to meet mission requirements. The operating time of the thruster was limited to 15 minutes during the cycle so that a large number of cycles could be achieved in a reasonable time period. This paper presents the results of an accelerated cycle test of an 8-cm EMT prototype which successfully completed more than 5000 on-off cycles.

APPARATUS AND PROCEDURE

The thruster used in the accelerated cycle test was originally a SIT-8 with the discharge chamber modified to conform to the 8-cm EMT design. The modifications were necessary to reproduce the performance characteristics of the 4.5 mN EMT. Foremost among the changes were the length of the discharge chamber, the baffle size, the size and number of cathode pole piece flow diversion ports, the magnetic field strength, and the axial position of the main cathode. A detailed description of the EMT design is given in reference 7. Figure 1 is a photograph of the 8-cm ion thruster prior to start of the accelerated cycle test.

The ion beam extraction system consisted of dished electrodes with a chemically etched low open area (18.6 percent) accelerator grid for improved propellant utilization efficiency. Table I gives electrode dimensions, which were approximately the same as for the EMT (18.9 percent accelerator grid open area). The grids were closely spaced with a gap of 0.64 mm at the perimeter. Figure 2 is a photograph of the ion thruster with the ground screen enclosure removed and shows a full view of the accelerator grid.

The main and neutralizer cathodes were integral parts of SIT-8 Cathode-Isolator-Vaporizer (CIV) and Neutralizer-Isolator-Vaporizer (NIV) assemblies, respectively, and were essentially identical in design to the EMT cathodes. Noteworthy features were the Al_2O_3 flame-sprayed heaters, the alkaline-earth oxide coated rolled tantalum foil inserts and the enclosed keeper electrode geometry. Construction details are given in reference 6. The CIV and NIV mountings were modified to make these assemblies compatible with the changes in discharge chamber. The NIV assembly mounting can be seen in figure 2. A well defined insert activation procedure, described in reference 6, was applied to both cathodes prior to the start of the test. Following an exposure to atmosphere, the same activation procedure was used to recondition the inserts before resuming the test.

Thin metal samples were placed at a number of locations inside the discharge chamber prior to the cycle test in order to determine, by means of weight changes, potential sputter erosion deposition effects resulting from thruster start-up and short term operation. The sample locations were among those determined by previous studies (ref. 8) to be primary sites for discharge chamber sputter erosion and deposition. Figure 3 is

a view of the discharge chamber which shows samples mounted on the anode, end plate, cathode pole piece flange and the baffle.

Figure 4 is a schematic showing the power supply arrangement for the accelerated cycle test. This figure also defines the ion thruster test parameters and their symbolic representation. The power supplies were laboratory types similar to those used in previous 8-cm ion thruster life tests (ref. 3). Critical supplies, such as the discharge and keeper, were regulated to closer than 1 percent. Voltages and currents associated with thruster operation were read from panel meters calibrated to within a few percent prior to the start of the test. Selected parameters such as J_B , ΔV_I , V_{CK} , and V_{CV} were monitored on a multichannel strip chart recorder.

The thruster was cycled once an hour. Each cycle consisted of a 10-minute cathode preheat, 15 minutes steady state thruster operation, and 35 minutes off time. Figure 5 is a simplified schematic of the cycle sequence control circuit and shows the order in which the power supplies were actuated during thruster start-up. Cathode starting consisted of the 10-minute preheat of the cathodes and vaporizers, followed by the application of a high voltage pulse to the keeper electrodes simultaneously with 35 V dc from the keeper supplies for discharge maintenance. The high voltage pulse had a maximum amplitude of 5 kV, which is the EMT power processor limit, and a rate of voltage rise of approximately 0.6 kV/ μ sec. Tip heater power was increased in increments of 1 to 2 W as needed during the course of the cycle test to keep the breakdown voltage below the 5 kV limit. A higher level of keeper current was used for starting (360 mA) than for operation (60 mA) of the main cathode.

Operation of the thruster was performed at a constant beam current (J_B) of 72 mA and a net ion accelerating voltage of 1220 V, which corresponded to a thrust of about 4.5 mN. The mercury flow to the discharge chamber, and hence J_B , was controlled by maintaining a constant difference of near 30 V between the anode voltage (ΔV_I) and main keeper voltage (V_{CK}). The discharge current (J_E) and main keeper current (J_{CK}) were generally held constant at around 0.5 A and 60 mA, respectively. The J_E , J_{CK} , and $\Delta V_I - V_{CK}$ levels were occasionally adjusted during the cycle test to maintain J_B at 72 mA. The neutralizer was operated at constant keeper current (0.5 A) and a vaporizer power corresponding to a steady state Hg flow rate of approximately 6 mA. Figure 6 shows traces of J_B , ΔV_I , V_{CK} , and V_{CV} during a typical cycle. Less than three minutes was required for the beam current to stabilize at 72 mA. This was accomplished by starting the main cathode at approximately the same Hg flow (80 mA) as that used during thruster operation, thereby requiring little change in the main vaporizer temperature. In contrast, the neutralizer vaporizer required almost the entire 15 minutes of thruster operation to cool from a temperature corresponding to a starting flow of 25 mA to a temperature corresponding to an operating level of around 6 mA. Both the main and neutralizer cathodes were operated without tip heat except during start-up.

Table II summarizes the nominal thruster parameter operating values.

Some of the thruster components had previously undergone approximately 1500 cycles prior to start of the 5200 cycle test. Table III summarizes the approximate number of total cycles and hours of operation for the principal thruster components. The cycle test was performed in a 1.5- by 6.1 m vacuum facility where the pressure was maintained in the low-to-mid 10^{-6} torr range. The ion thruster faced a 1 m diameter target located approximately 3 m downstream.

RESULTS AND DISCUSSION

Time History of Test

Figures 7 and 8 show the time history of 5200 cycle test of various thruster parameters which were not controlled and were most indicative of the main and neutralizer cathode starting characteristics. Each of these parameters will be discussed below in terms of the thruster component performance.

Cathode-Isolator-Vaporizer (CIV) Performance. -

Cathode: The starting capability of a cathode can be characterized by the applied cathode tip power and starting voltage required for a given propellant flow rate. The required starting high voltage and cathode tip power are shown in figure 7. Several of the initial cycles did not require the high voltage pulse and started with just the 33 volt open circuit voltage of the cathode keeper supply. After the initial cycles, however, figure 7(a) shows that the starting voltage was only a few hundred volts until about cycle number 1200 when a large increase was observed. The reason for this sudden increase is not known. As determined by the preset conditions, the cathode tip power was raised during preheat after the starting voltage had reached 5 K volts. The cathode tip power (fig. 7(b)) was increased from 20.2 to 21 watts after cycle number 1205. This reduced the starting voltage to approximately 2.5 K volts, but during subsequent cycles the voltage again increased.

Several more cathode tip power increases were necessary until the 26 watt level was reached at cycle number 2080. Subsequently, the starting voltage remained relatively low (1 to 2 kV) for the remainder of the test.

The keeper voltage (fig. 7(c)) remained relatively constant during the life test. The keeper voltage was 7.8 volts after the sharp rise of the starting voltage at 1250 cycles and rose to only 8.3 volts at the end of the test. This indicated that no significant deterioration of the cathode took place due to cyclic operation.

The preceding observations indicate that the main cathode and its heater performed satisfactorily during the accelerated cyclic life test.

The 26 watts of tip power required in the life test is well below the 36 watts for cathode starting available from the EMT power processor.

Isolator: - The isolator leakage current was not monitored during the test. However, post-test inspection of the isolator surface gave no indication of surface contamination.

Vaporizer: - No problem was encountered with the main cathode vaporizer and its heater during the cyclic test. The vaporizer temperature that was required to provide the necessary flow rate through the main cathode remained constant during the life test which indicated that the flow transmission coefficient did not change.

Neutralizer cathode-isolator-vaporizer (NIV). - Figure 8 shows the behavior of the neutralizer cathode during the life test. As seen in figure 8(a), the neutralizer cathode starting voltage gradually increased with time as compared to the sudden increase observed in the main cathode behavior. The 5 K volt limit was reached at approximately 3000 cycles. At this point, similar to the main cathode, several tip heat power (fig. 8(b)) increases were required to reduce the starting voltage. At about 27.5 watts the starting voltage decreased appreciably. Because the test was terminated at 5200 cycles, it is not known whether at this power level the starting voltage would have remained low (1 to 2 kV) as it did for the main cathode at 26 watts.

The keeper voltage (fig. 8(c)) was reasonably constant with voltage levels ranging from 18.0 to 20.5 volts during the test. The neutralizer floating potential (fig. 8(d)) appeared to increase very slowly by around 2 to 3 volts over the test.

Isolator: - The isolator leakage current was not monitored during the cyclic test, but again inspection after the test revealed no evidence of damage or surface contamination.

Vaporizer: - As with the main cathode vaporizer, no variation of flow conductance was observed of neutralizer vaporizer during the test.

Accelerator current. - Figure 9 shows the accelerator current during the life test. The current decreased from 0.24 to about 0.14 mA during the first 1200 cycles. The corresponding current during a 15 000 hour test (ref. 1) was -0.2 mA. The lower value of the current in this test can be attributed to the higher mass utilization in this test due to the small hole accelerator grid (SHAG) used. The SHAG geometry does result in higher direct ion impingement than the larger hole accelerator grid used previously (see section in Post-Test Inspection). However, the increased propellant utilization efficiency resulted in a lower net accelerator grid current than for the large hole geometry.

Thruster performance. - The thruster performance did not change appreciably during the life test. Table IV lists the various thruster

performance parameters at three points in the life test. The mass utilization was constant to within one percent at cycles 897 and 4881.

Overall, the thrusters performance during the cyclic test was very satisfactory. No grid arcs were observed during the entire test.

Post-Test Inspection

Initial inspection of the cyclic life test thruster revealed considerable deposition and spalling of back-sputtered material on the front (downstream) side of the ground screen and accelerator grid (fig. 10). Such deposition is typical in tests operated in small vacuum facilities without frozen mercury targets.

Visual inspection of components inside the discharge chamber indicated that they were in excellent condition. Detailed inspection and documentation proceeded further with the thruster disassembled. Thruster components were weighed to determine net deposition or sputtering rates. Deposition and sputtering sites were also evaluated by the small badges placed inside the discharge chamber. Deposited material at several sites was chemically analyzed so that sputtering sources could be identified.

The test was initiated before sputtering rates of the 30-cm diameter thruster were found to be affected by trace amounts of vacuum facility background gases. In reference 9 the sputtering rates were found to decrease by almost a factor of three as the pressure was increased from 1×10^{-7} to 1×10^{-6} torr. (The pressure in this test was about 2×10^{-6} torr.) Therefore, the sputtering and deposition rates measured in this test are probably lower than those expected in space. The following discussion will be limited to those thruster components which were considered to be major sputtering or deposition sites.

CIV. - Close inspection of the cathode revealed no appreciable change of orifice size or excessive sputter erosion. Also, the outside surface of the isolator was found to be relatively clean of contaminants.

NIV. - Similarly, the neutralizer cathode exhibited no visible signs of deterioration. Generally, no significant wear was noted for any component of the neutralizer assembly.

Accelerator grid. - A photograph of the downstream side of the accelerator grid (fig. 11) shows the deposition on the outer periphery of the grid. A close-up photograph (fig. 12), reveals the charge exchange pattern in the center of the accelerator grid. Profileameter measurement of charge exchange pits indicated a maximum erosion rate of

about 1.8×10^{-6} cm/hr. Some uncertainty exists in this measurement because of some unknown time of thruster operation during pretesting. Examination of the charge exchange erosion region showed that these pits were not of uniform size. Figure 13 shows the blistered deposition at the outer edges of the accelerator grid as well as the notching of the outer holes of the grid. Because of the considerable deposition observed on the outer areas of the grid, it is likely that the flux of back-sputtered material reduced the charge exchange erosion rates at the center of the accelerator grid. Chemical analysis of the deposit shown in table V indicates that the main source of the back-sputtered material on the grid was tank wall material (SS-304; 65 to 71 percent Fe, 18 to 20 percent Cr, 8 to 12 percent Ni, ~2 percent Mn) and gate valve material (Al). The thickness of a spalled off chip from the front face of the ground screen was measured to be $\sim 1 \times 10^{-4}$ cm. The notching has been observed before in life tests (ref. 3). Figure 9 shows that the notching probably took place early in the test as deduced from the high level of accelerator current during the first 1250 cycles of the test. Figures 14 and 15 show the upstream side of the accelerator grid before and after the cyclic life test. The photographs show clearly the erosion patterns around each accelerator hole, and explain most of the 0.432 gram weight loss suffered by this grid. The upstream erosion is due to high energy ion impingement on the accelerator grid. A profileameter trace of a typical hole in the center of the grid is presented in figure 16. An erosion rate of about 5 to 7×10^{-7} cm/hr was measured. This rate did not vary much along the grid radius. The width of the erosion area, however, decreased with radius (as seen in the photograph). This erosion mechanism is not considered to be severe, even if some uncertainty exists due to effects of facility environment on this sputtering rate.

Profile thickness measurements (fig. 17(a)) of the accelerator grid did not indicate any significant overall grid thickness changes during the test.

Screen grid. - Photographs of the screen grid holes (fig. 11) show no sign of deterioration. Profileameter measurements (fig. 17(b)) also showed no significant sputtering taking place. The net weight gained (0.206 g) was probably due to deposits on the outer periphery area upstream and downstream sides of the screen grid. The upstream deposition originates from discharge chamber erosion and the downstream side deposits result from direct ion impingement on the upstream side of the accelerator grid. There was no evidence of blistering or spalling of these deposits.

Again, it is difficult to assess the exact effect of the facility environment on the sputtering rate of the upstream side of the screen grid. Because of the lower current density and double ion production rate in the 8-cm diameter thruster as compared to the 30-cm thruster,

estimates indicate that screen grid sputtering should not be a severe problem. Also, spectrographic measurements of the 8-cm thruster discharge operated in 1 to 2×10^{-7} torr range were taken and tend to substantiate this conclusion.

Discharge chamber components. - Table VI shows the weight change rates of the main components of the discharge chamber. In this table, the deposition or sputtering rate ($\text{gm}/\text{cm}^2\text{-hr}$) was calculated when an average deposition or sputtering area was sufficiently defined. A deposition rate in A/hr was calculated when an average density of a deposit was obtained by chemical analysis.

As expected, the anode had the highest deposition rate. Visual inspection revealed no blistering or spalling from the wire mesh covered anode. Several flakes were found on the anode which were thought to have come from the deposition badges on the anode which had not been treated to increase their adherence characteristics. Table VII shows the deposition and sputtering as measured from the badges. These measurements show a somewhat lower deposition rate for the anode than the average deposition rate seen in table VI. This may be due to some spalling from the badges mentioned before. Table V shows the chemical analyses of these deposits from the anode at two locations. It is apparent that molybdenum from the upstream side of the accelerator grid and probably some sputtering from the center of the upstream side of the screen grid make up more than half of the deposit on the anode.

The end plate underwent a net deposition during this test, contrary to observations in other previous life tests. This difference may be explained by the higher sputtering rate of the small hole accelerator grid and higher backspattered material due to the small vacuum facility. The plasma sprayed tantalum end plate surface appeared in excellent condition with no spalling present.

As expected, the tantalum baffle also underwent sputtering. The badge measurements indicate that the downstream baffle sputtering rate was about three times as that of the upstream side. The two methods of measuring the sputtering rates of the baffle show reasonable agreement.

Under certain conditions, where the geometry is rather simple, deposition rates can be calculated from a sputtering source (ref. 10). Such a configuration may be assumed of the sputtered baffle and deposited anode. If the baffle is assumed to be a point source, a cosine sputtering distribution yields an arrival rate of 2.6×10^{-9} cm of tantalum from the baffle to the downstream anode position. A small additional contribution to this rate is expected from the tantalum clad cathode pole piece. [The measurement of this rate was not successful.] The chemical analysis of the deposit on the badge on the anode at that point indicated an

arrival rate of tantalum of 4.3×10^{-9} cm/hr. This value is in fair agreement with the measured deposition rate.

A total anode deposition layer of about 6μ (10^{-4} cm) is estimated for a 7500 hour mission. This rate of deposit can be easily accommodated without spalling by the present thruster design. The operation of the thruster in environments free of facility environmental effects would increase this rate. If this increase were similar to that obtained for the 30 cm thruster, a deposit of about 18 to 30 μ would have been expected. Deposits of 30 μ have shown to be nonspalling (refs. 11 and 12) and adherent layers of up to 100 μ have been observed in the 30-cm thruster.

The sputtering rates of the screen and accelerator grids and of the baffle do not appear to be life-limiting phenomena for the 8-cm thruster.

CONCLUDING REMARKS

An 8-cm ion thruster similar to the EMT design, successfully completed 5200 on-off cycles. Each cycle included 15 minutes of operation at a 4.5 mN thrust level. The main and neutralizer cathode tip heater powers and keeper voltages remained well within acceptable limits and the changes in thruster performance were small over the duration of the 5200 cycle test. Sputter erosion of the accelerator grid, baffle, cathode pole piece, and screen pole piece was observed but was not considered as sufficient to impair performance in a mission requiring 7500 hours of thruster operation. Erosion elsewhere in the discharge chamber was negligible. The performance and integrity of the cathode tip heaters was verified. It is concluded that on-off cyclic operation by itself does not appreciably degrade starting capability or performance of the 8-cm EMT.

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TABLE I. - DIMENSIONS OF ION BEAM EXTRACTION ELECTRODES.

HEXAGONAL HOLE ARRAY

Grid	Open area, percent	Grid thickness, mm	Hole diameter, mm	Center-to-center spacing, mm
Accelerator	18.6	0.51	1.0	2.21
Screen	68.0	.38	1.91	2.21

TABLE II. - NOMINAL THRUSTER PARAMETER OPERATING VALUES

Beam current, J_B	72 mA
Discharge voltage, ΔV_I	40 V
Discharge current, J_E	0.54 A
Main keeper voltage, V_{CK}	8 V
Main keeper current, J_{CK}	0.06 A
Neutralizer keeper current, J_{NK}	0.5 A
Neutralizer keeper voltage, V_{NK}	18 V
Accelerator voltage, V_A	300 V
Net accelerating voltage, V_I	1220 V
Accelerator grid current, J_A	0.14 mA
Neutralizer floating potential, V_G	-15 V

TABLE III. - APPROXIMATE NUMBER OF CYCLES AND HOURS OF OPERATION

COMPLETED BY VARIOUS THRUSTER COMPONENTS

Component	Cycles	Hours of operation
CIV	5200	1300
NIV	6700	1700
Grids	6700	1700
Discharge chamber	6700	1700

TABLE IV. - PERFORMANCE PROFILE

Number of test cycles	0	896	4680
Net accelerating potential, V	1220	1220	1220
Accelerator potential, V	-300	-300	-300
Beam current, mA	72.0	72.3	72.0
Main cathode flow rate, mA equiv.	80	80	81
Neutralizer flow rate, mA equiv.	6	6	6
Beam power, w	86.9	87.1	86.8
Discharge power, w	19.0	15.5	17.8
Component power			
Accelerator drain, w	0.3	0.3	0.2
Main cathode			
Heater, w	0	0	0
Keeper discharge, w	0.6	0.4	0.6
Vaporizer, w	4.3	4.1	4.5
Total main cathode power, w	4.9	4.5	5.1
Neutralizer			
Heater, w	0	0	0
Keeper discharge, w	10.7	9.3	9.7
Vaporizer, w	1.8	1.8	1.8
Total neutralizer power, w	12.5	11.1	11.5
Coupling power, w	1.1	1.1	1.1
Total input power, w	124.7	119.6	122.5
Power efficiency, percent	70.0	72.8	70.8
Utilization efficiency, percent	83.7	84.1	82.8
Thrust, ^a mN	5.12	5.12	5.07
Specific ^a impulse, sec	2908	2919	2874

^aNeglecting beam divergence and double ionization effects.

TABLE V. - COMPOSITION OF DEPOSITS ON THRUSTER COMPONENTS

Thruster component	Major constituents of deposits, percent ^a						
	Fe	Cr	Ni	Hg	Al	Mo	Ta
Ground screen mask	28.3	7.0	4.2	24	17.4	3.4	1.9
Anode (upstream)	4.3	1.1	1.0	11	1.2	52.0	6.5
Anode (downstream)	3.4	0.8	0.5	24	1.5	59.8	5.6

^a Accuracy reported: ± 5 percent RSD, except Hg which is ± 50 percent.

TABLE VI. - WEIGHT ANALYSIS OF THRUSTER COMPONENTS

	Weight change rate		Average sputtering or deposition rate, Å/hr
	g/hr	g/cm ² /hr	
Screen grid	+1.2×10 ⁻⁴	+6.3×10 ⁻⁷	+8.2
Accelerator grid	-2.6×10 ⁻⁴		
Anode	+1.7×10 ⁻⁴		
Baffle support	-7.7×10 ⁻⁶		
CIV spacer spool	+4.4×10 ⁻⁶		

TABLE VII. - WEIGH ANALYSIS OF DEPOSITION/SPUTTERING
BADGES OF THRUSTER COMPONENTS

Component	Weight change rate, g/cm ² -hr	Average sputtering/ deposition rate, Å/hr
Anode (downstream)	+6.0·10 ⁻⁷	+7.7
Anode (upstream)	+5.0·10 ⁻⁷	+6.1
Baffle (downstream)	-2.1·10 ⁻⁶	-12.5
Baffle (upstream)	-6.3·10 ⁻⁷	-3.8
End plate	+3.9·10 ⁻⁷	
Cathode pole piece flange	+3.3·10 ⁻⁷	
Screen pole piece	-3.1·10 ⁻⁶	

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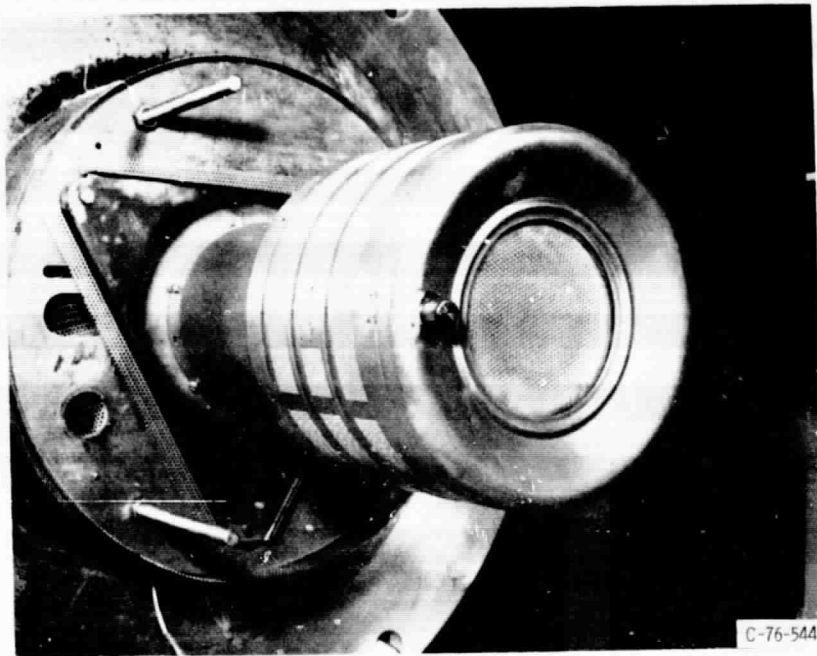


Figure 1. - 8-Cm ion thruster prior to start of 5200 cycle test.

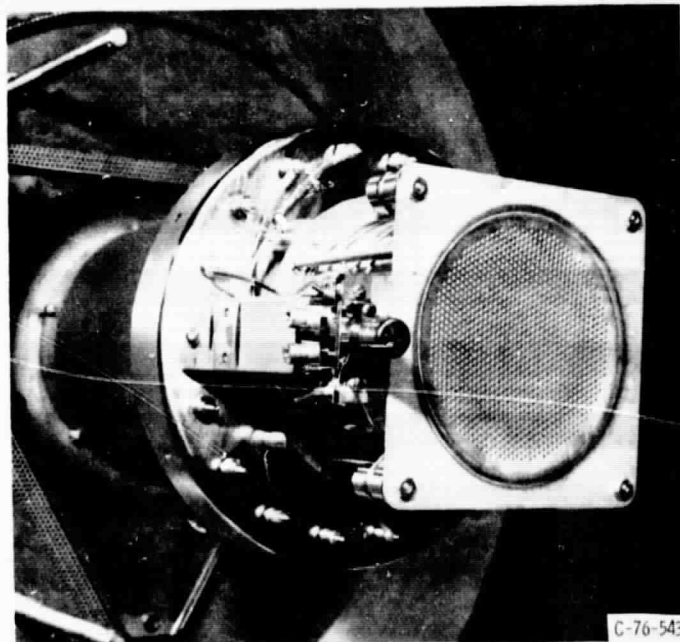
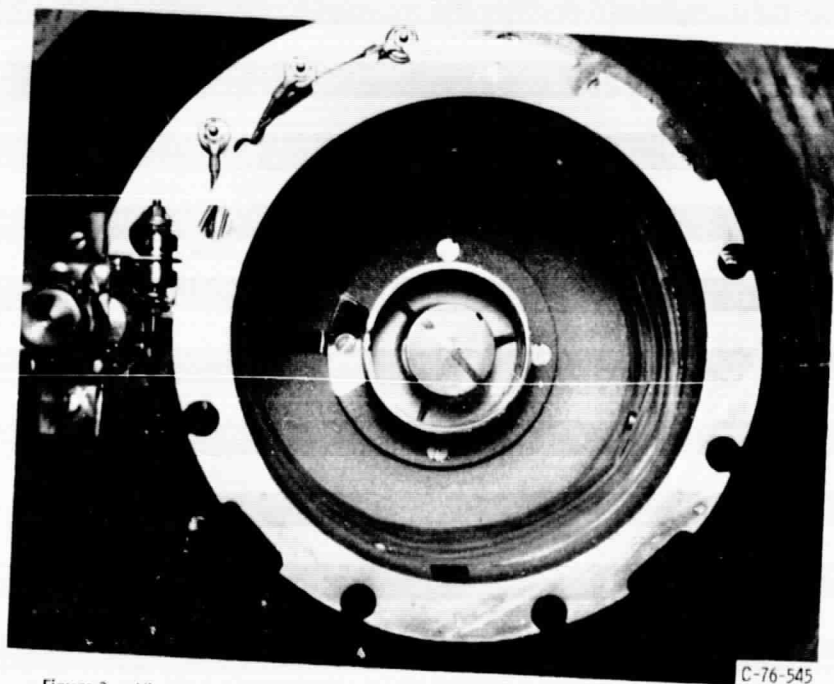
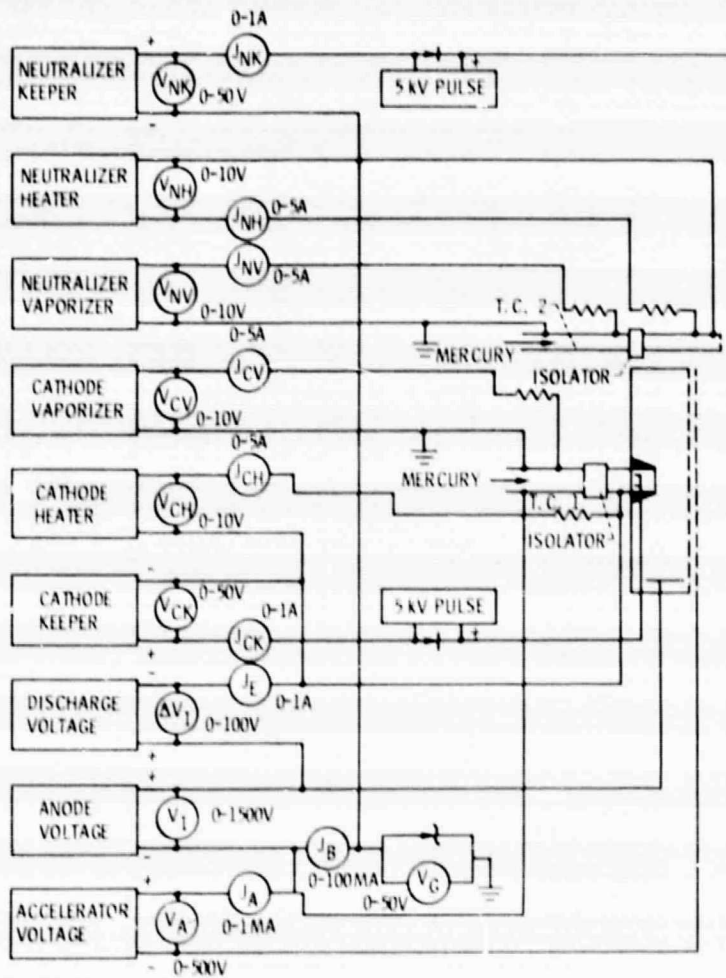


Figure 2. - Ion thruster with ground screen removed showing neutralizer mounting and accelerator grid.



C-76-545

Figure 3. - View of discharge chamber showing some of sputter erosion-deposition samples.



NOTES: T.C. - IRON CONSTANTAN THERMOCOUPLE

Figure 4. - Schematic showing power supply arrangement for accelerated cycle test.

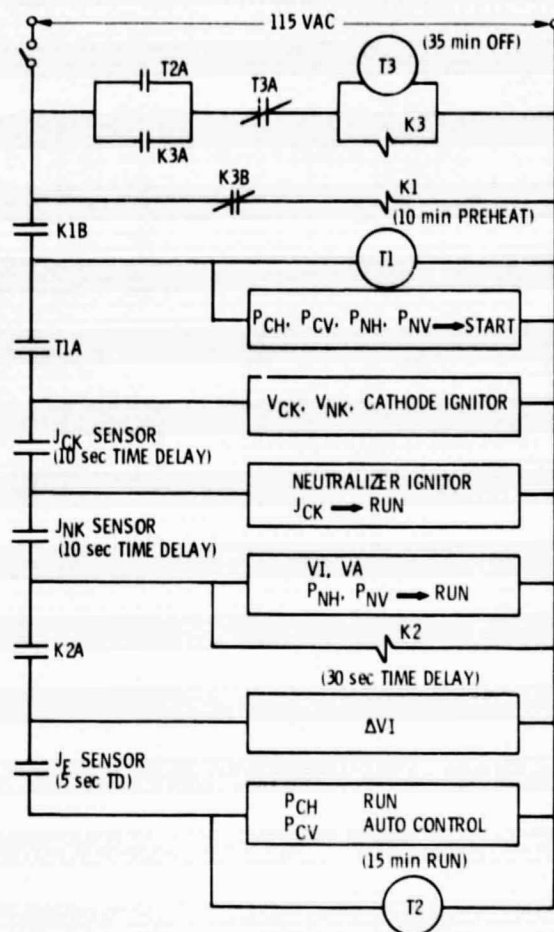
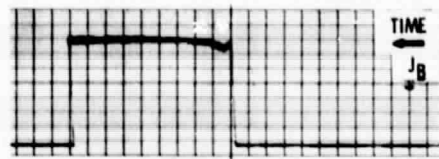


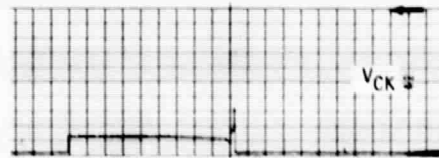
Figure 5. - Simplified schematic of cycle sequence control circuit.



(a) BEAM CURRENT (J_B).



(b) DISCHARGE VOLTAGE (ΔV_1).

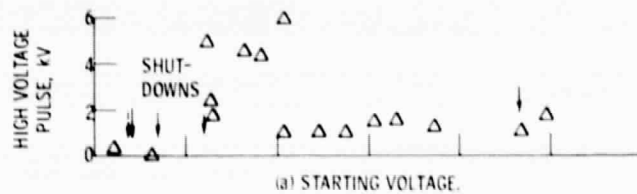


(c) CATHODE KEEPER VOLTAGE (V_{CK}).

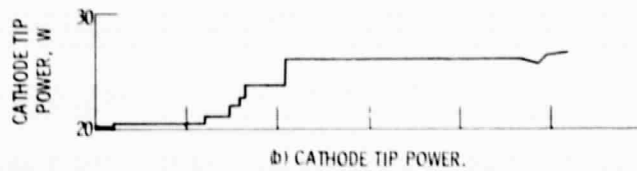


(d) MAIN VAPORIZER HEATER VOLTAGE (V_{CV}).

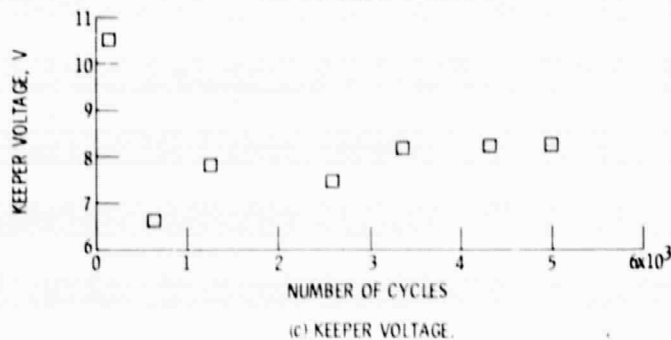
Figure 6. - Thruster parameters during a typical cycle.



(a) STARTING VOLTAGE.



(b) CATHODE TIP POWER.



(c) KEEPER VOLTAGE.

Figure 7. - Time history of main cathode performance parameters.

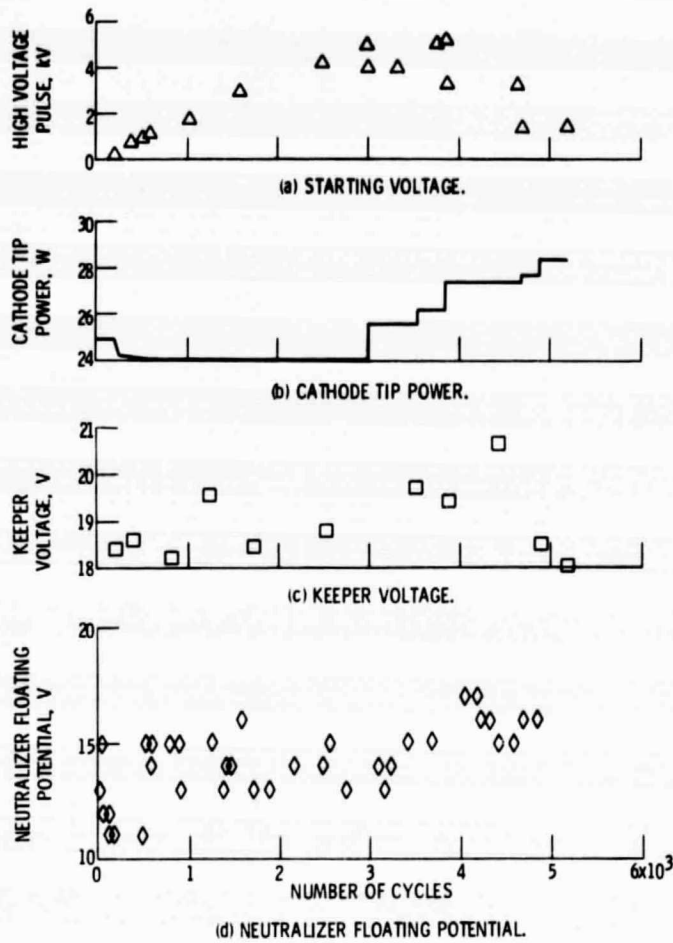


Figure 8. - Time history of neutralizer cathode performance parameters.

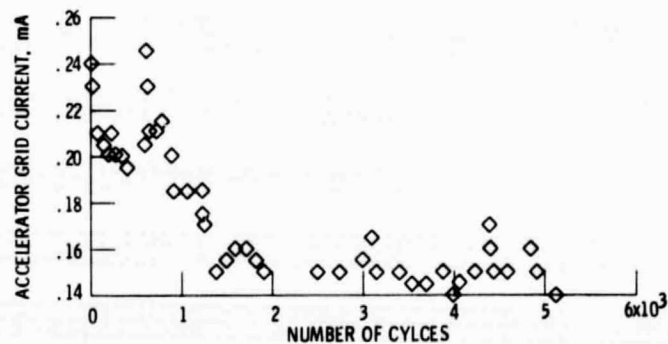


Figure 9. - Time history of accelerator grid current.

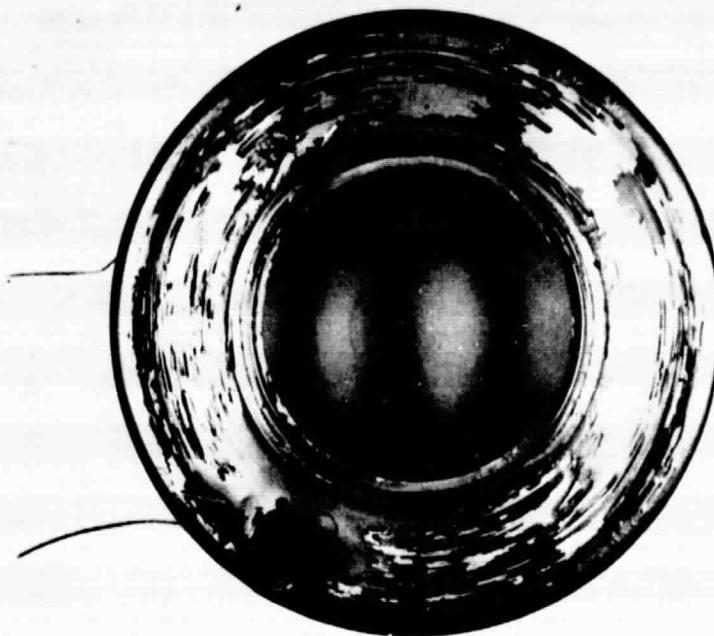


Figure 10. - Deposition on ground screen mask.

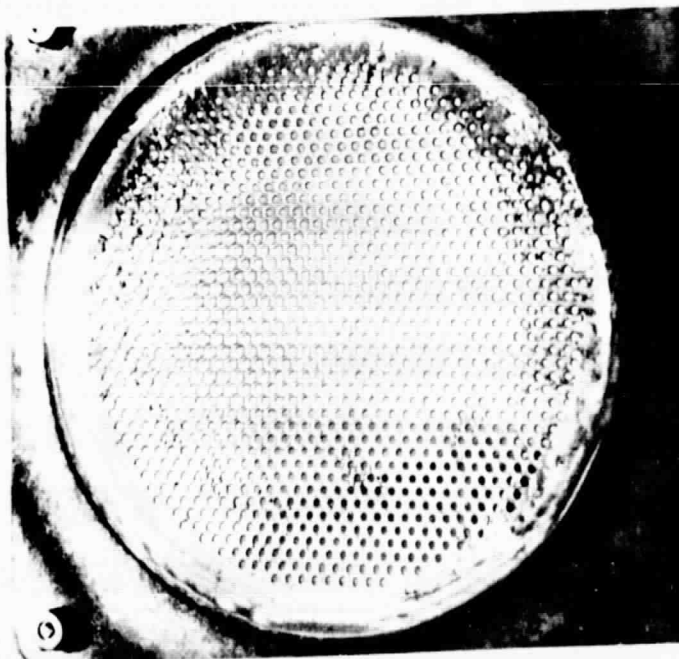


Figure 11. - Downstream side of accelerator grid after 6700 cycles.

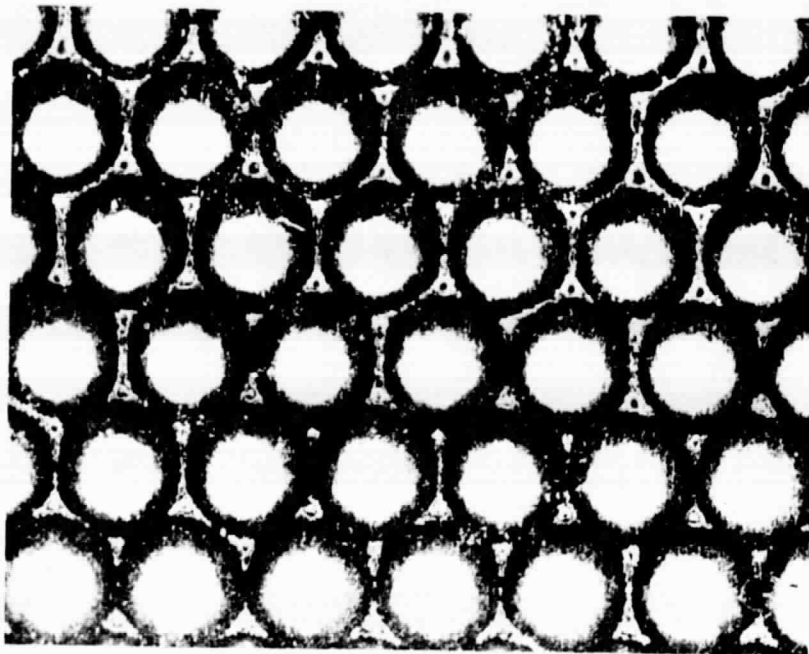


Figure 12. - Charge exchange erosion at center of accelerator grid.



Figure 13. - Deposition at the edge of accelerator grid.

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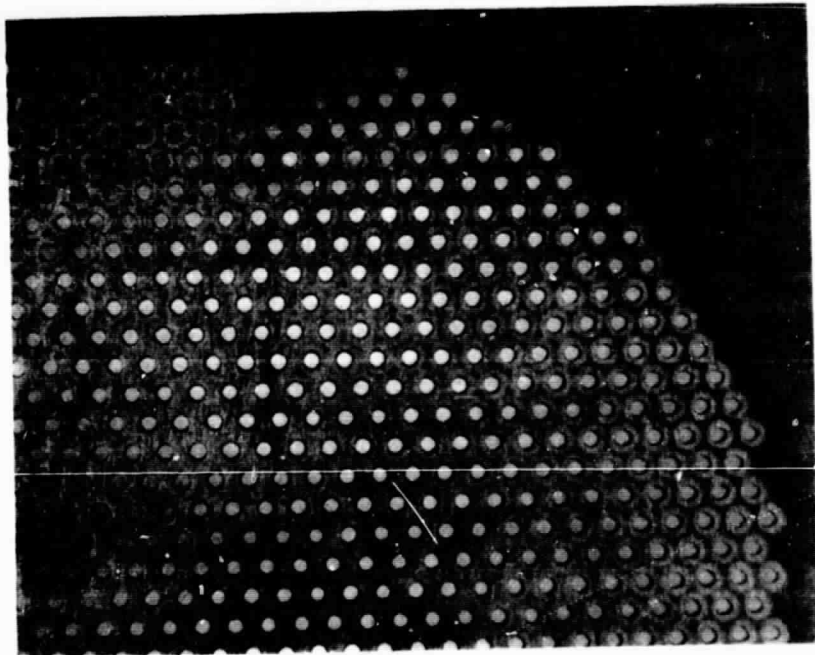
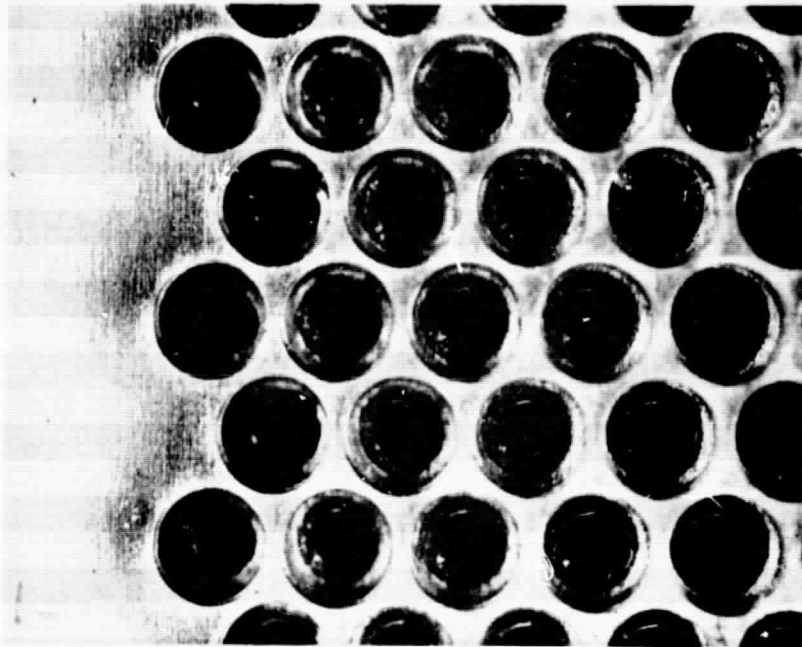


Figure 14. - Upstream side of accelerator grid before test.

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(a) EDGE OF ACCELERATOR GRID.



(b) CENTER OF ACCELERATOR GRID.

Figure 15. - Upstream side of accelerator grid after 6700 cycles.

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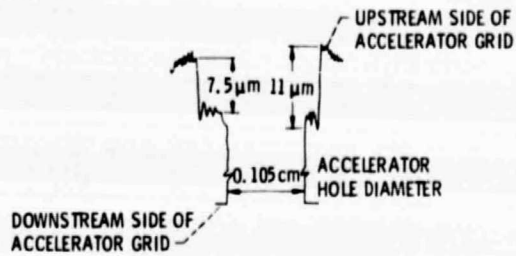


Figure 16. - Direct ion impingement sputtering of upstream side of accelerator grid in ~1700 hours.

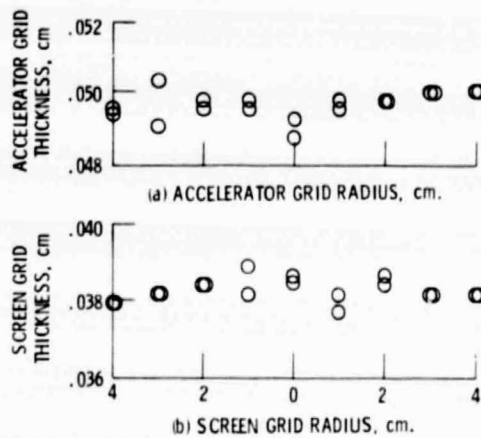
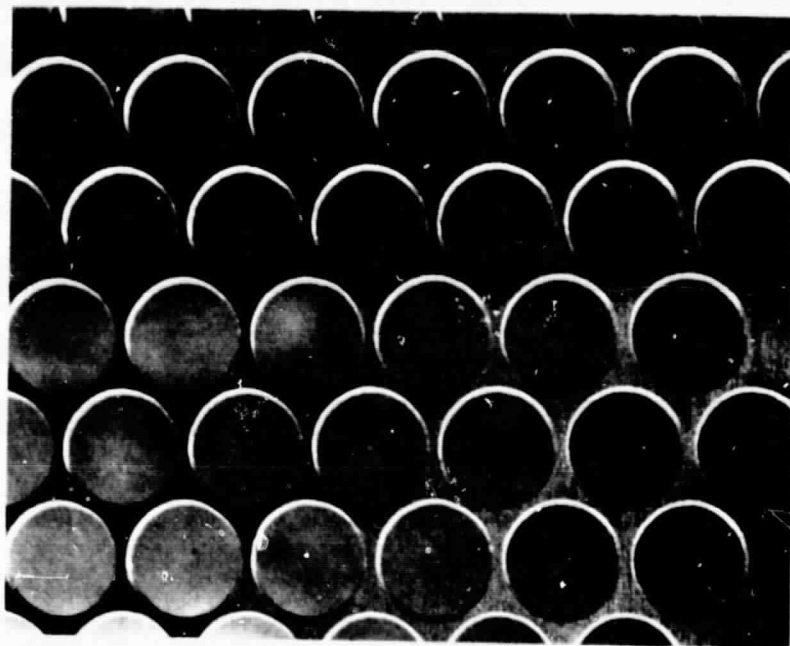
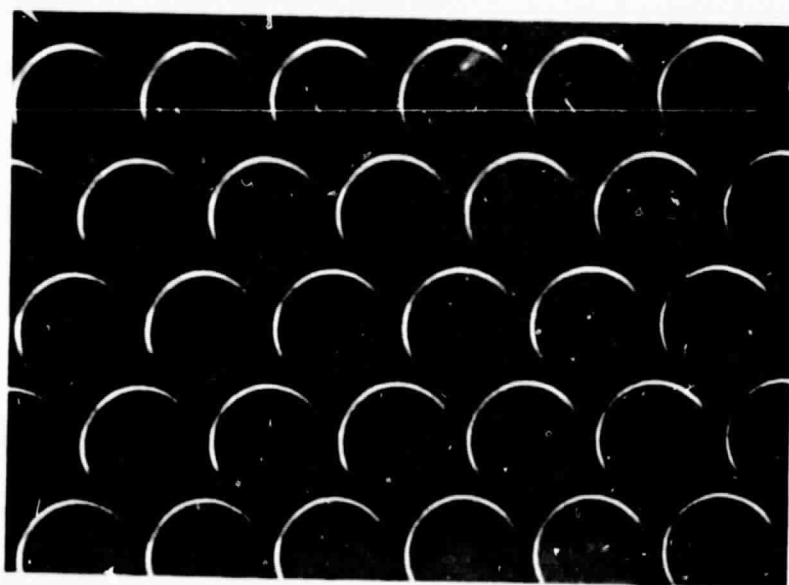


Figure 17. - Grid thickness after the test (across two diameters).



(a) EDGE OF SCREEN GRID.



(b) CENTER OF SCREEN GRID.

Figure 18. - Upstream side of screen grid after 6000 cycles.